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Framework for Integrating Production System Models and Product Family Models

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Abstract

As the demand for product customization increases globally, companies must increasingly manufacture individually configured products, which stresses the traditional business processes and manufacturing systems. Although previous research indicates potentials in integrating product and process models, few practical implementations of this are found partly due to lacking systems integration. This paper proposes a framework for integrating existing information repositories for manufacturing system and product family model information. By integrating this information, manufacturing information can improve the product configuration process and product configuration information can support the manufacturing process.

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Keywords: mass customization, ontology, co-platforming, product model, process model.

1. Introduction

In most industries, practitioners are reporting an increasingly stronger competition due to shorter product life cycles and requirements for shorter time to market, while also being faced with increased cost focus induced by competitors and steadily increasing product variety and environmental sustainability [1, 2]. One means to address this is through efficient handling of variety in products as well as in processes, a discipline broadly known as complexity management [3-5]. Developing platforms for products as well as processes has historically proven effective to manage complexity, with one of the most well-known examples being the product platforms developed and applied in the automotive industry [6, 7].

Product platforms, process platforms, as well as modularity within these domains in general are often highlighted as enablers of changeable manufacturing, which addresses some of the challenges outlined above [8, 9]. A multitude of publications address how to develop product platforms and manufacturing platforms, and a small part of this literature addresses the concept referred to as co-platforming [10, 11]. The basic concept of co-platforming is to match the solution space of products – the product platform, with the capabilities of the manufacturing system – the manufacturing platform. A related concept is co-evolution, [12-14], which suggests that the evolution of products and manufacturing systems should be closely coordinated.

When developing platforms individually, co-developing platforms or co-evolving a formal representation or documentation of products and processes is a prerequisite in order for designers to create solutions based on the platforms. Much of the information needed to represent products and processes is present in most companies, however, it is often scattered in a variety of different enterprise IT systems, such as Enterprise Resource Planning (ERP), Product Data / Lifecycle Management (PDM/PLM), Manufacturing Execution Systems (MES) and product configurators. Some information is usually also represented in text documents or spreadsheets. The fact that product and process information is scattered around different systems and documents implies that it is very difficult to aggregate this information and establish formal relations between product information and process information representing the platforms within these two domains.

The discipline product modelling or product family modelling has produced a number of methods for aggregating product information, or more specifically product variety

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information into a single model [15]. Although some research has also focused on modelling the manufacturing system, little research is published on how to model the products and manufacturing system in one aggregated model with the relations between the two domains. Even less research addresses doing this based on existing data in a company's enterprise IT systems.

When modelling generic structures of products and processes, the concept of ontologies is relevant as it provides mechanisms for modelling specific entities using a common language. Previous publications have addressed this using ontologies for linking product and process information [16-18], however, at a rather conceptual level or focused on defining one universal, generic ontology. In this research, we define an ontology as an information model defining the central concepts and their interrelations necessary for addressing a specific problem in a specific context. Hence, in this context, an ontology will define the basic vocabulary and structure necessary to model products and processes. When applying ontologies, thereby applying a "common language", what can be achieved is that information follows a common structure. When information follows a common structure, this information can more easily be processed and utilized for various purposes.

The research presented in this paper explores how the development of company specific ontologies can contribute to aggregating existing data from enterprise IT systems to establishing a single source of data model of products and processes.

2. Proposed approach for modelling

We propose an approach, which focuses on modelling the range of components in a company's product portfolio, as well as the equipment and the processes performed by this equipment, based on company specific ontologies. We propose modelling a company specific product-process ontology, which defines the different types of processes and components which may be found in a given company, as well as the characteristics and capabilities of these types. This ontology also specifies how component characteristics relate to process capabilities, thus, defining how manufacturability of different types of equipment can be inferred from the relations between process and component characteristics.

Fig. 1 shows the most basic data structure for such an ontology using Unified Modelling Language (UML) class diagram notation. The classes within the dashed area form a "generic ontology", which specifies the component types and process types within a manufacturing system, whereas the classes outside the dashed area represent "instances" of the generic types, i.e. specific components (with specific item numbers), and specific equipment and its processes. Below, we describe each class with examples and relations to other classes.

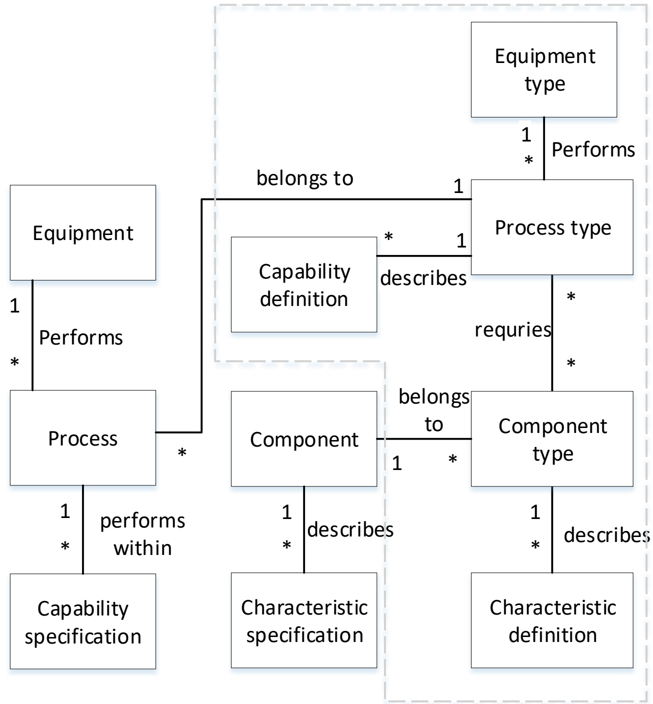

Fig. 1 UML Class diagram for product-process ontology.

2.1. Generic Ontology

Within the dashed area, the classes represent the product-process ontology. The class "Component" represents the different types of components produced in the production system, e.g. gear, axle, pipe etc. The class "characteristic definition" is used for defining which characteristics are used to describe a component sufficiently for being able to specify requirement for the manufacturing processes. Characteristics may include physical attributes, as well as processing requirements. Examples of this could be physical dimensions, weight, tolerances, degrees of freedom in processing, etc.

The class "Component type" relates to the class "Process type". This relation describes which processes are needed to manufacture each component type. This relation must also contain information about the sequence of processes. The class "Process type" itself represents all the different process types found in the manufacturing system being modelled, e.g. casting, drilling, milling etc. This class again relates to multiple "capability definitions" which define for each process type, which properties that are relevant to define for the processes, in order to be able to determine the manufacturability of components on this process. As an example, for a milling process this could be maximum and minimum dimensions, number of axes, minimum and maximum revolutions per minute (RPM) etc. By modelling the objects in such context specific ontology based on the classes shown in Fig. 1, a link is established between the properties of processes and the properties of components on a generic level, meaning that the specific relations between these properties are defined on a generic level. As an example, for a component type "axle", we may define that an axle requires the processes cutting, turning, milling, and drilling in that order. Also we may define for this component type that the component characteristics length and diameter relate to the process capabilities maximum and minimum length, width and height for the milling process, and the component characteristic "tolerance" may relate to the process capability "precision for the milling process type.

The intent of modelling using the approach presented in this paper is to model specific components, and specific equipment and processes, and determine which equipment may manufacture which components. However, by modelling the classes describing process types and component types and their relations, this only needs to be modelled once, and the relations are defined for all instances of components and equipment generically.

When modelling an actual manufacturing system and products, the classes will be instantiated as objects, where e.g. each object represents a specific process type, capability definition etc. Fig. 2 illustrates an example of how component types and process types are linked generically. The diagram illustrates objects, which are instances of the classes shown in the class diagram in Fig. 1

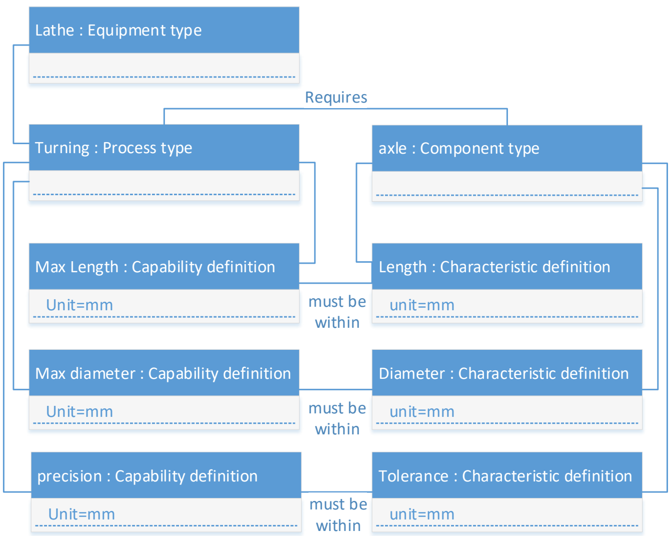

Fig. 3 UML Object diagram showing example of a company specific product-process ontology

3. Specific equipment and components

The classes outside the area marked by the dashed line in Fig. 1 are used to represent specific instances of the component types and process types. These specific instances are described as defined for the types they belong to. The class "Component" represents actual components being manufactured (i.e. one per item number). The class "Characteristic specification" represents the actual characteristics of this specific component. The characteristics that must be specified for each component are governed by the underlying characteristic definition belonging to each component type, and hence each "characteristic definition" under a certain "component type" must be specified specifically for each instance of the component. As an example, when modelling a specific component, e.g. an axle, the component type defines that the characteristics length, diameter, and tolerance must be specified for any axle, but when modelling the actual components, these characteristics are assigned values, e.g. length=1200mm, diameter=25mm and tolerance ±0.1mm, which constitute the "characteristic specification" objects. This is illustrated in Fig. 3.

Fig. 2 UML object diagram showing example of specific equipment and component applying the ontology

The "Equipment" class represents actual machines in the manufacturing system, e.g. machines, tools etc.; physical entities in the production system with capabilities of transforming materials contributing to the production of components. Examples of equipment might be a CNC mill, lathe, drill, assembly robot etc. The class "Process" represents the actual processes which equipment in the production may perform. Each specific process is only performed by one piece of equipment, however, some equipment may be able to perform multiple processes, e.g. a computer numerically controlled (CNC) mill may be able to both milling and drilling.

The "Capability specification" class specifies the actual process capabilities for a specific piece of equipment, which basically represents the "process window" for the equipment. As with the components characteristics, each capability which must be specified for each process is governed by the capability definition objects for the process types. As an example, a process "turning" may be defined by maximum and minimum length and diameter, and precision. The turning process may then be performed by a specific lathe in the manufacturing system, for which the capabilities are specified as minimum length=10mm, maximum length=1500mm, minimum diameter=3mm, maximum diameter=400mm, precision=±0.05mm. Fig. 3 illustrates this using objects which are instances of the types illustrated in Fig. 2. No associations are defined between the process capabilities and component characteristics, since these associations are defined on a generic level for the process types and component types. The underlying structure of capabilities and characteristics for the specific processes and components is governed by the structure seen in Fig. 2, where the specific process types and component types are shown.

4. Implementation

When modelling manufacturing systems and the components they produce, this must likely be done as an iterative process, where components are modelled one at a time. Every time a new component type is encountered, this must be modelled prior to modelling the actual component. This also applies to modelling equipment and processes. The classes and relations shown in Fig. 1 should be implemented in a database-based IT system implementing this data structure.

As indicated in the introduction, one inherent challenge of many previous modelling approaches is that they are document based, or focused on a stand-alone information system. If implementing the approach proposed in this paper, attention should be paid to ensure a single source of data consistency, meaning that the users modelling products and processes should only model information, which is not already present in other IT systems. Typical Enterprise IT systems which hold this type of information includes ERP, MES, PDM and PLM systems. ERP systems will typically hold master data about components, i.e. component names, item numbers, as well as certain component characteristics such as weight, dimensions etc. These systems will also often specify item types or item groups which may indicate candidates for component types.

They will also hold information on which equipment is presently used for manufacturing them. However, this is typically defined on a specific level, i.e. specific routes with specific machines for specific components. However, during the modelling process this can be used as input for modelling this generically. Hence, the implementation of the information model proposed in this approach will contain existing enterprise IT systems, as well as a database linking to these systems. This database holds information about component types, process types, their interrelations, and additional component characteristics that are not readily available in the existing systems.

The fact that some characteristics of components may be available in various enterprise IT systems, possibly in multiple systems, e.g. ERP and PLM, makes the implementation more challenging, compared to implementing a single database system. This implies that the component types and characteristic definitions in some cases must specify where the values of these characteristics may be found, i.e. the path to the attributes in the ERP system. This means that for the actual specific components, some characteristics may be inputted and maintained in the enterprise IT systems. However, for characteristics not present in the enterprise IT systems, they must be defined in a separate database. Another option would be to introduce the proposed data structure in one of the existing IT systems, e.g. the PDM systems, where significant amounts of product data may be present. This would however require the PDM system to also hold information about production equipment and processes, which may reside more naturally in an ERP or MES system.

The component type part of the ontology is very likely to be completely company specific; however, equipment and process types are more likely to be generic across companies. Different efforts have been made to define classifications or ontologies of manufacturing processes [19-21], which each have slightly different focus including or excluding certain groups of processes.

It is possible that one of these process classifications could be imported and applied directly as a process ontology, as they are completely generic. However, it is possible that the process ontology would contain far more processes than actually necessary. Furthermore, the capabilities of the processes may include too many details compared to what is actually necessary to match components with processes, thus requiring excessive effort when implementing new equipment in the database. However, the classifications may be more useful as a gross list of processes and process capabilities, which can be implemented in the company specific ontologies as needed.

4.1. Modelling process

The process of modelling products, production systems, and equipment is largely dependent on the characteristics of the company implementing the system. However, generally it must be expected to be a highly iterative process. As with other projects which could potentially change the business processes of a company, it should be considered whether a “big bang” implementation or a gradual implementation should be pursued. With a “big bang” approach, a company would undertake a project modelling all products and processes. With a gradual implementation, a model of products and processes would be introduced as new products are developed and new processes are introduced as a result of a new product or a replacement of existing equipment.

In both cases, an iterative process is relevant. When modelling e.g. a component, the engineer doing this will search for a suitable component type. If this component type exists, the engineer would simply assign values to the characteristic specifications. If the component type does not exist, another workflow must be followed, introducing a new component type, defining the characteristic definitions and their relations to process types and capability definitions. The same consideration applies to new processes and equipment.

5. Applications

The modelling approach we propose in this paper is not intended for one specific application, but rather is a generic product-process modelling framework. Since such database would ideally contain information about any component and any process within a company and the relations between these, this information could be used for a variety of purposes. Below, we present a few examples of applications for this framework.

The information in a system based on this approach would be able to serve as a representation of a company’s manufacturing platform. This means that if a new product is developed, and the components are described according to the component types in the ontology, it can easily be determined if a company already has equipment able to manufacture these components, and not least which specific equipment would be able to do this. For small companies, this information is not apparently relevant as production engineers will likely have an overview of the existing equipment, however, for large enterprises with hundreds or thousands of machines, this is more relevant as it can help determining if new equipment should be purchased or existing equipment can be utilized. The opposite scenario would also potentially be relevant. This may also be relevant in the product design phase, where design for manufacturing activities may depend on the capabilities of the existing equipment in a company. In this case, product designers designing a new component where the component type has already been defined in the ontology, will be able to easily look up the existing capabilities and thereby determine which variety can be manufactured on which equipment. In a situation, where a company wishes to buy new equipment, the description of product characteristics can be aggregated to determine which capabilities are necessary if e.g. machines are replaced due to obsolescence or wear or simply capacity expansion.

Finally the information may be utilized for production planning. In many cases, companies have several machines that are able to perform the same processes, however, at different speed and cost. Given the information in the database, a complete mapping of different component-process combinations can be generated. This mapping can be utilized in production planning for optimizations, by e.g. assigning components to equipment producing at the global optimum cost, a task impossible to do if the possible combinations of components and processes are unknown.

6. Discussion

The approach presented in this paper is work in progress, and a number of simplifications or delimitations were made to communicate the principles more clearly. One simplification which will need to be addressed in an actual implementation is the fact the we look only at binary relationships, i.e. relations between two objects, such as the relation between one characteristic for a component and one capability of a process. In some cases, a certain capability may be linked to a combination of two characteristics. As an example, a handling robot is able to lift a greater mass, the closer the object is to its base. This type of relation is not possible in the proposed structure, but nothing prevents it from being implemented in an extended ontology. Furthermore, the approach looks only into manufacturing components, and does not address multi component assemblies and assembly processes. This would also be possible by extending the ontology, but is left out for simplicity. Also, we address the individual equipment and processes as stand-alone processes. This implies that we disregard the fact that some machines and processes are located in cells or manufacturing lines in combination with other equipment. Finally, the approach does not take into account manufacturing speed or any economy issues. Moreover, we do not regard this as a major challenge to implement in a future ontology.

7. Conclusions

In this paper we have proposed a framework approach for modelling company context specific ontologies. Based on these ontologies, the specific components, equipment, and processes can be modelled, along with the component characteristics and process capabilities. Linking the component types with process types on a generic level provides opportunity to match specific components with equipment with appropriate capabilities. Furthermore, it enables analyzing and querying the solution space of component characteristics, as well as process capabilities in design projects or equipment purchasing processes. If modelling components and processes as proposed in this paper, companies will gain knowledge of their component and process solution space, which was previously unavailable but highly applicable to several different problems. Since previous research has focused on either creating one generic ontology encompassing all production processes, or has been very specific for specific processes or products, the novelty of this work lies in proposing an approach for establishing company specific ontologies. Furthermore, a novel contribution in this research is the integration between a product ontology and process ontology, also on a company specific level, as well as an implementation oriented information model, allowing fairly low barriers for implementation. Future research beyond what is presented in this paper will include extending the ontology to address the limitations mentioned above. Furthermore, a process will be developed to support the development of the ontology and mapping of the actual components and equipment. Finally, an actual production system with its components will be mapped to validate the approach in a real life context.

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